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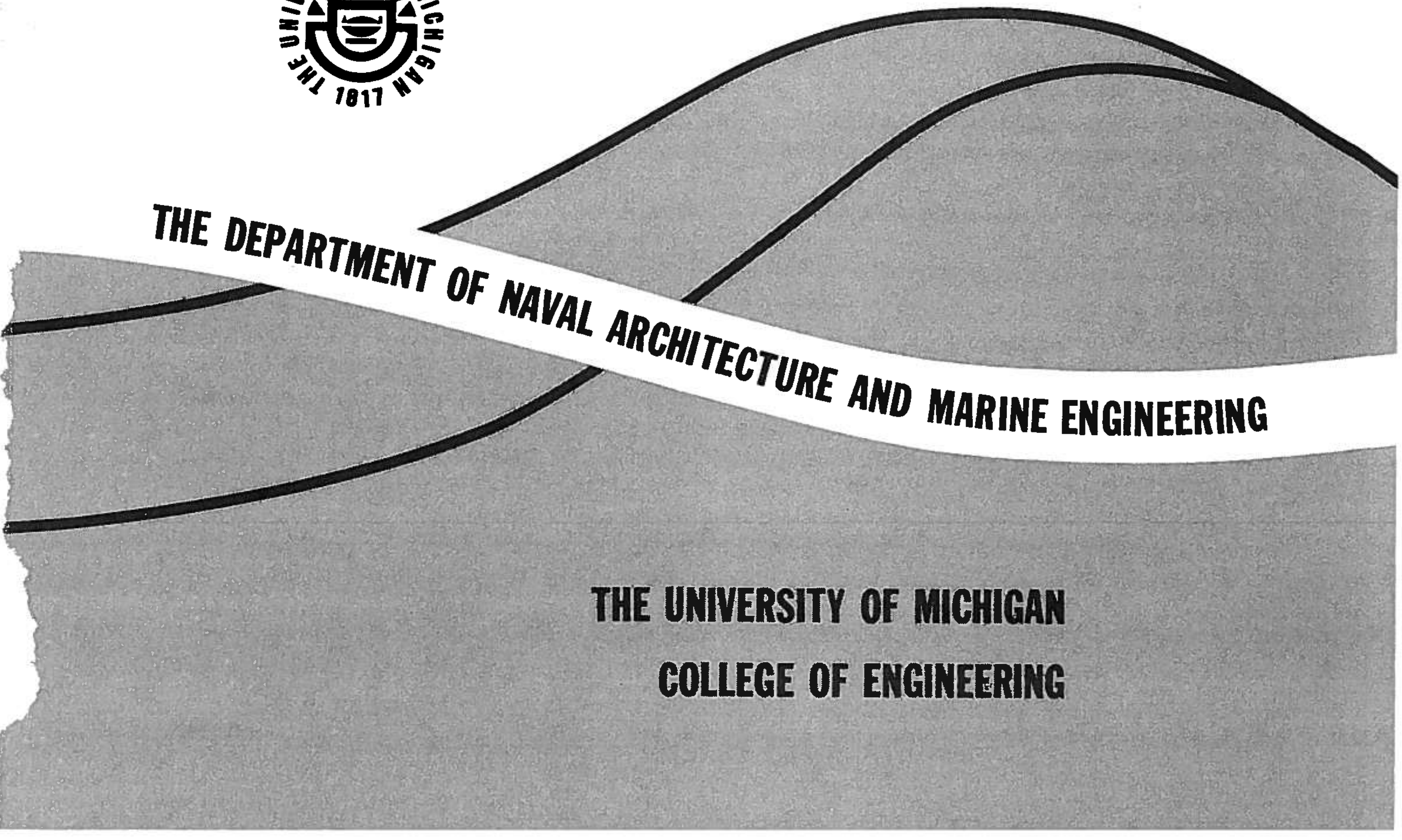

THE DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

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ABSTRACT

The results of an experimental investigation into shallow water ship motions are presented. The experiments were conducted in two parts. In the first part, the change in form of sinusoidally generated waves as they travel in shallow water were measured. The results are presented as changes in the Fourier harmonics with distance from the wave maker. Comparisons with theoretical predictions from the Korteweg-de Vries equation are made and show good correlation.

In the second part of the experiments, measurements were made of the surge, heave and pitch motions of a tanker model in response to shallow water waves. Because the exciting waves are not sinusoidal, the waves and motion responses were Fourier analyzed. The first harmonic amplitudes were then considered to be the equivalent linear responses. The experimental results are compared with theoretical predictions made by a slender body theory of shallow water ship motions. The surge theoretical results are in reasonably good agreement with the experiments. The heave and pitch agreement is poor.

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INTRODUCTION

In recent years there has been increased interest in shallow water ship motions due to the advent of extremely large, deep draft tankers and bulk carriers. In many parts of the world these ships are unable to enter harbors and must unload and load their cargos in unprotected waters. They are subsequently subject to ocean waves and their corresponding motions can be of critical importance in the design of mooring and off-shore unloading systems.

In order to predict the motions of ships in shallow water, two theories have been proposed. The first, due to Kim (1968), is a modified strip theory that accounts for the presence of the bottom. Using the usual strip theory coefficients for the equations of motion, Kim computes the sectional added mass and damping for a two dimensional section with a bottom present. Kim only presents results for heave and pitch in head seas.

A different approach is followed by Tuck (1970) who uses the method of matched asymptotic expansions. Assuming that the vessel is slender and that the wavelengths are long compared to the water depth, expressions for the added mass, damping and exciting forces are found for zero forward speed.

The results of the two theories may be compared to a simple first order theory. In the first order theory, surge is uncoupled from the heave and pitch modes. For surge, the first order theory requires a balance between the Froude-Krylov exciting force and the natural inertia force due to the mass of the ship. For heave and pitch, the first order theory involves the Froude-Krylov exciting force and the hydrostatic restoring forces. The advantages of this theory are that no hydrodynamic problems need be solved to compute the motions. In deep water, at zero forward speed, the first order theory predicts the ship motions very well. For a Series 60, C_B=.70, hull, Kim's finite depth strip theory results are almost identical to the first order results for wavelengths greater than a ship length. For wavelengths about half the ship length Kim's results show a substantial increase in the heave and pitch motion.

Calculations of shallow water motions using Tuck's theory [see Beck and Tuck (1972) and Beck (1973)] reveal marked differences from the results computed by strip theory. Around wavelengths equal to the ship length there are large increases in the heave and pitch motions over the first order theory. For much shorter wavelengths, the results are close to those predicted by first order theory. Strictly speaking, Tuck's theory is not valid in this region because the incident waves are no longer shallow water waves. However, one may hope that the theory still gives reasonable results in the high frequency region. The surge motion is approximately the same as given by the first order theory and both tend to become increasingly large as the wavelength of the incident wave increases.

In order to gauge the accuracy of the theoretical predictions, comparisons with experimental results must be made. Unfortunately, no experimental results for ship motions in shallow water were available. Thus, it was decided to conduct a limited set of experiments. Only the vertical plane motions (surge, heave and pitch) were to be measured for head seas. The effects of varying water depth and linearity with wave height were also to be investigated.

The experiments were much more difficult than originally envisioned due to the inherent nonlinearities of shallow water waves. In Part I of this report, the nonlinearities associated with shallow water waves are discussed. In addition, results from the experimental measurements of the degeneration of sinusoidal waves with distance from the wavemaker are presented.

In Part II, the experiments to measure the vertical plane motions of a tanker model are described and results presented.

Comparisons with theoretical computations are also shown. Due to the nonsinusoidal character of the incident waves, all experimental measurements were Fourier analyzed and only the first harmonic components are used in comparisons with theoretical predictions.

Part I - Shallow Water Wave Generation

It is known that sinusoidal waves in shallow water are unstable and will degenerate fairly rapidly. In order to conduct the ship motion experiments, a knowledge of this process is essential. Therefore, a series of wave experiments were conducted to measure the changes in wave form as the sinusoidal waves propagated down the experimental basin.

Both the wave and motion experiments were conducted in a 40' by 40' shallow water basin. The waves were generated by a plunger type wavemaker. The plunger was rectangular in shape with dimensions 13'-8" long and 8" wide. The stroke (and the wave amplitude) could be varied by changing a mechanical linkage. Frequency was altered through the use of a variable speed clutch.

For the wave experiments, a channel 13'-8" wide and running the length of the diagonal of the basin was constructed. At one end the wavemaker was placed. At the other end a beach consisting of expanded polyvinyl chloride sheets with a slope of 1 to 7 was made. Reflections from the beach were tested for and found to be nonexistant. It was found from water depth measurements along the channel that the bottom had slight variations. The water depth used for the wave experiment was .6' and the bottom variations were less than 5% of the depth. It is assumed that the bottom variation had little or no effect on the experimental results.

Measurements of the wave profiles were taken in the center of the channel at distances of .75, 6.1, 11.7, 16.7, 21.0 and 26 feet from the leading edge of the wavemaker. The wave amplitudes were measured using a sonic wave probe. Because of the lack of wave probes, the wave profiles at the different locations were not measured simultaneously. One probe was placed at a single location and waves of different frequencies generated. The probe was then moved to the next location and the same frequency waves regenerated. Repeatability was checked and found to be satisfactory. The frequencies at which the plunger was run are shown in Table 1. Also shown in Table 1 are the nominal shallow water wavelengths corresponding to the given frequencies.

Table 1 - Experimental Wave Frequencies and Nominal Wavelengths at a Depth of .6 feet.

Wave Frequency (rad/sec)	Nominal Wave Length (ft)
2.55	10.8
2.98	9.26
3.45	8.00
4.19	6.59
4.91	5.62
5.66	4.88

The nominal wavelengths are calculated using the linear shallow water dispersion relation:

$$\omega^2 = ghk^2$$

where

ω = wave frequency
g = acceleration of gravity
h = water depth
k = wave number
$= 2\pi/\lambda$
λ = wave length

Before presenting the results of the experiment, we digress for a moment to examine several theoretical results which help in understanding the nonlinear phenomenon. Korteweg and de Vries (1895) were one of the first to investigate nonlinear, shallow water phenomenon. They use a perturbation expansion on particle velocities to arrive at the classical equation which bears their name:

For the wave and motion experiments conducted at the University of Michigan, the values of σ ranged from about 3 to 25. Thus, the harmonic components can not be neglected. These conclusions also agree with Galvin, who presents plots of wave forms resulting from initially sinusoidal waves as functions of the parameters h/λ and ζ_o/h.

Bryant (1973) theoretically investigates the evolution of an initial sinusoidal wave train propagating in a uniform channel. The spatially periodic surface displacement is expanded in a Fourier series with time-dependent coefficients. Equations for the coefficients are derived from the nonlinear governing equations. Bryant presents numerical results which show that the magnitudes of the first and higher harmonics vary with distance down the channel. For the size and frequency waves we are interested in, the second harmonic may grow to 50% of the first harmonic.

Figure 1 is a sample print out (ω = 3.45 rad/sec, λ = 8 ft.) of the wave appearance as a function of distance down the tank. The top plot is the sinusoidal plunger motion. The next six plots are wave records taken at various distances down the tank measured from the leading edge of the wavemaker. The distances, nondimensionalized with respect to the nominal wavelength, are x/λ = .1, .75, 1.39, 2.0, 2.66, and 3.33 respectively. Note the evolution of the wave form as it propagates down the channel.

Figure 2 is a plot of the harmonic amplitudes at different distances down the tank for the wave profiles shown in figure 1. η_1 is the first harmonic, η_2 the second and η_3 the third. The harmonic amplitudes are normalized with respect to η_o , the theoretical sinusoidal wave amplitude generated by the wavemaker. An expression for η_o in terms of the plunger stroke and width is derived by Tuck (1972). The final result can be visualized by equating the volumn of water displaced by one half a

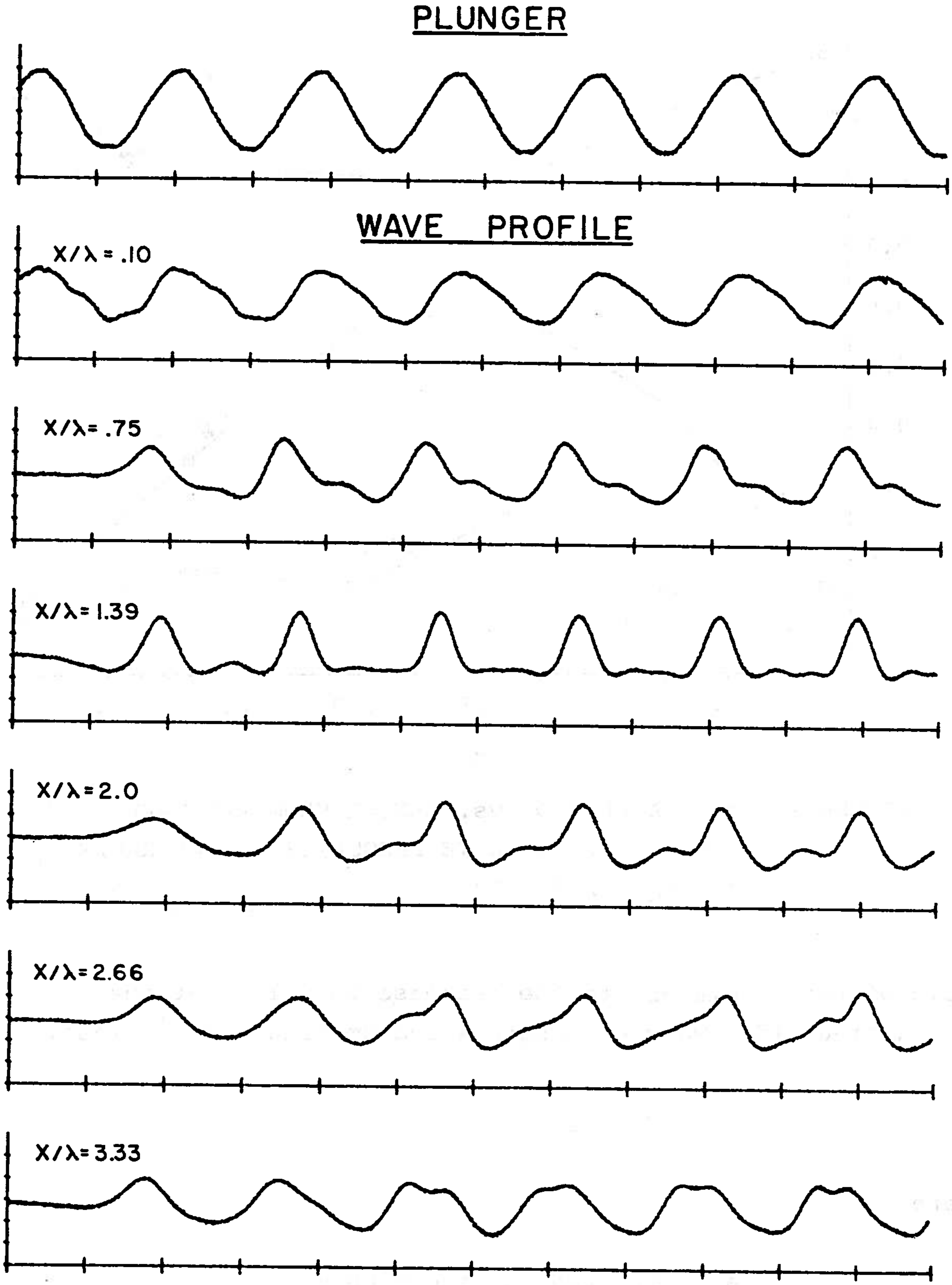

FIGURE 1. EXPERIMENTAL WAVE PROFILES VS. DISTANCE FROM WAVEMAKER

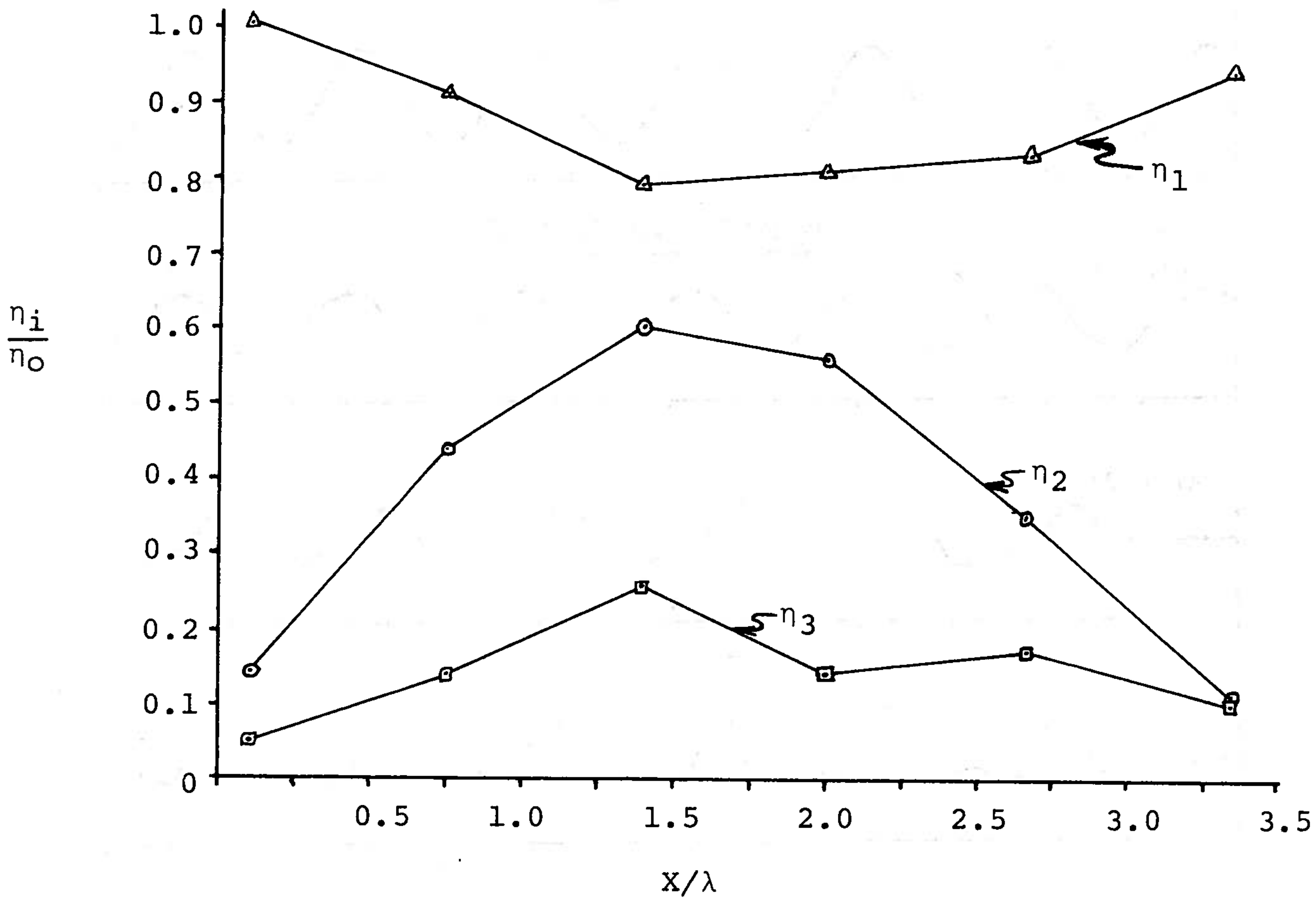

FIGURE 2 - WAVE AMPLITUDE vs. LENGTH FROM WAVEMAKER DEPTH - .6' , WAVE FREQUENCY - 3.45 RAD/SEC, $\sigma = \eta_o \lambda^2/h^3 = 22.5$

cycle of the wavemaker to the increase in volumn of one half a sinusoidal wave of length λ and amplitude η_o . Thus,

$$\eta_o = \frac{2\pi}{\lambda} \quad a \cdot b$$

where

a = amplitude of the plunger
b = width of the plunger

Comparing the results of figure 2 with the examples presented in Bryant, one can see the same general trend that the second and third harmonics grow initially and then decrease.

In figure 3 the first and second harmonics are plotted as functions of distance down the tank for the various wavemaker frequencies. As a check on the experimental results, it should be noted that the sum of the squares of the harmonic amplitudes is almost constant as one moves down the tank. The third plot in figure 3 is the parameter $\eta_2 h/\eta_o^2$ plotted against distance down the tank. The parameter $\eta_2 h/\eta_o^2$ is chosen because Tuck's (1972) analysis indicates that the resultant curve should be independent of frequency. As can be seen, this is indeed the case for x/λ less than 1.5. For x/λ greater than 1.5 the result no longer holds. The theoretical prediction is shown as a solid line in the third plot and is nearly linear with distance down tank. The curve parallels the experimental points, but shows a different origin. This is not too surprising since there are local effects not considered in the theory.

The correlation between the growth of the second harmonic predicted by Equation 2 and the experimental results is shown in figure 4 for $\omega=2.55$ and $\omega=2.98$ radians/sec. Near the wavemaker the correlation is very good. The origin of the Korteweg-de Vries equation has been shifted to give the best comparison of the slope with the experimental results. The shift can be justified since the exact origin of the sine wave generated by the wave maker is not known, due to local effects. The break down in agreement for larger values of x/λ is expected since the method of solution is valid for only small values of x/λ.

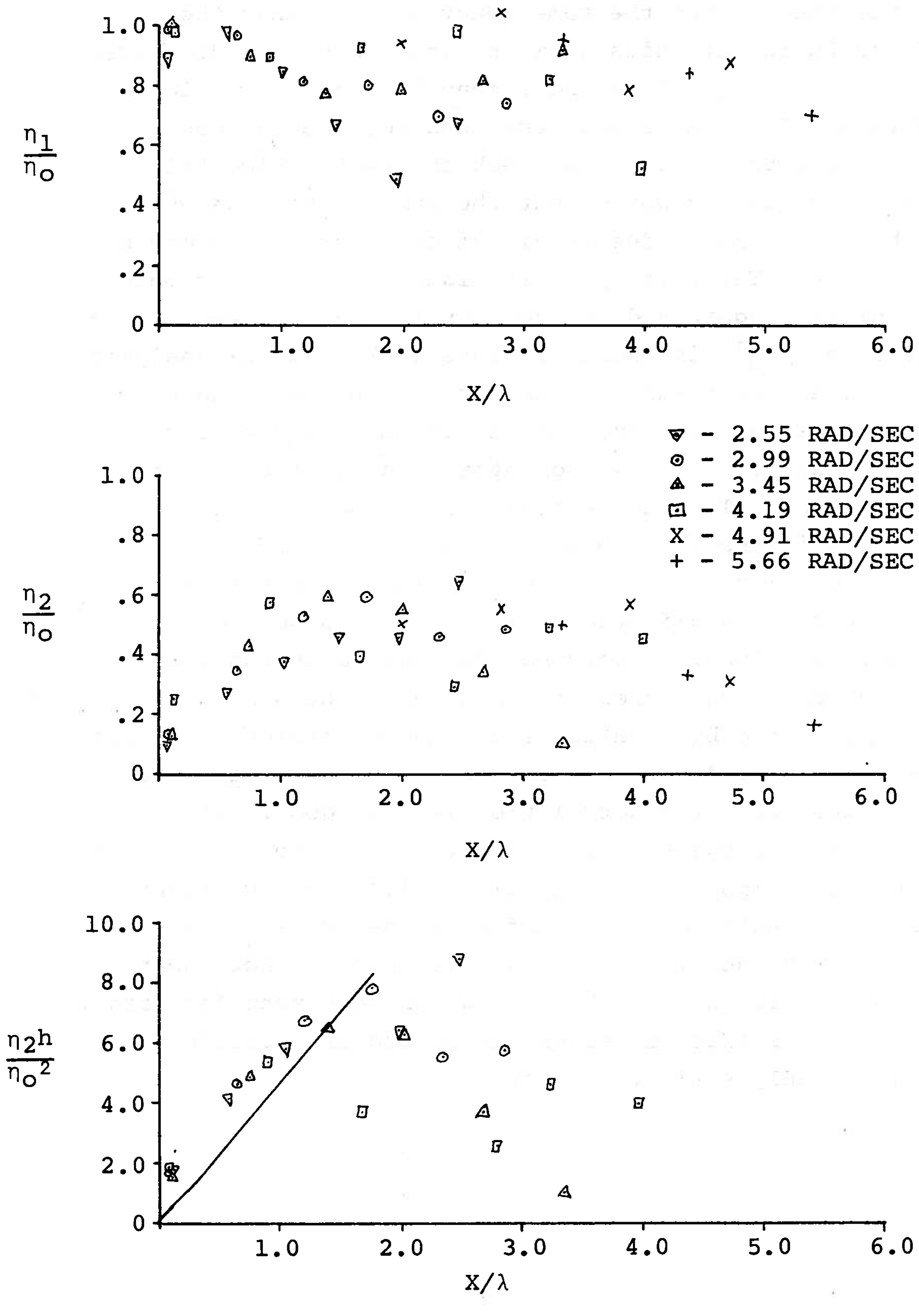

FIGURE 3 - NONDIMENSIONAL HARMONIC AMPLITUDES vs. DISTANCE FROM WAVEMAKER

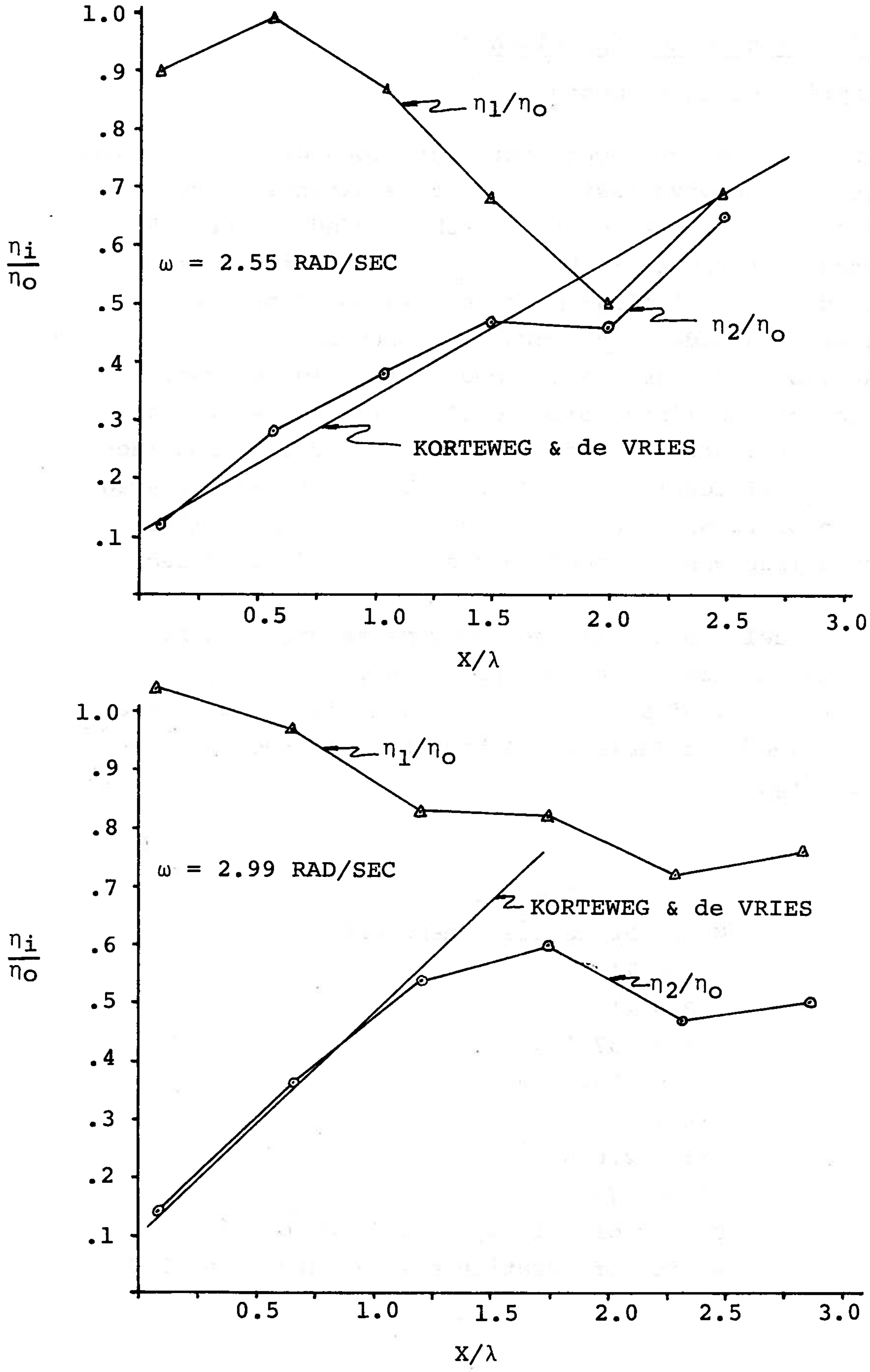

FIGURE 4 - GROWTH OF THE SECOND HARMONIC WITH DISTANCE FROM WAVEMAKER.

Part II - Ship Motion Experiments

Description of Experiments

The ship motion experiments were conducted in the same facility as the wave tests. The walls extending from the wavemaker were shortened and beaches added so that the model could be tested without interference effects from reflected waves. A diagram of the placement of the beaches, wavemaker and model are shown in figure 5.

As shown in figure 5 the model was held in position by three mooring lines composed of string and strips of rubber. The lines had a spring constant of .187 lbs/inch and an initial tension of .12 lbs. Two lines were placed at mid-ships running forward at an angle of about 16°. The third line was attached to the stern and ran directly aft.

The model chosen for the experiments was a tanker model which had been used for previous tests at the University of Michigan. The principle dimensions of the model are shown in Table 2. A body plan of the model is shown in figure 6.

TABLE 2

Model Principle Dimensions

$L = 7'$
$B = 1'$
$T = .375'$
$\Delta = 123.4$ lbs.
$L/B = 7$
$B/T = 2.666$
$C_B = .78$
Center of Gravity = .22' FWD of ⊗
Radius of Gyration = 1.67' about the C.G.

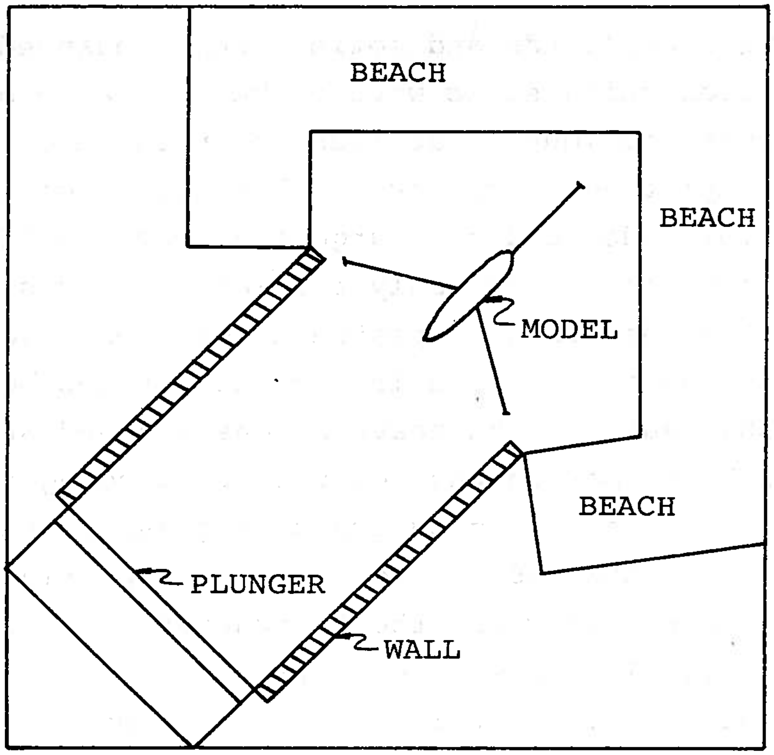

FIGURE 5 - EXPERIMENTAL BASIN LAYOUT

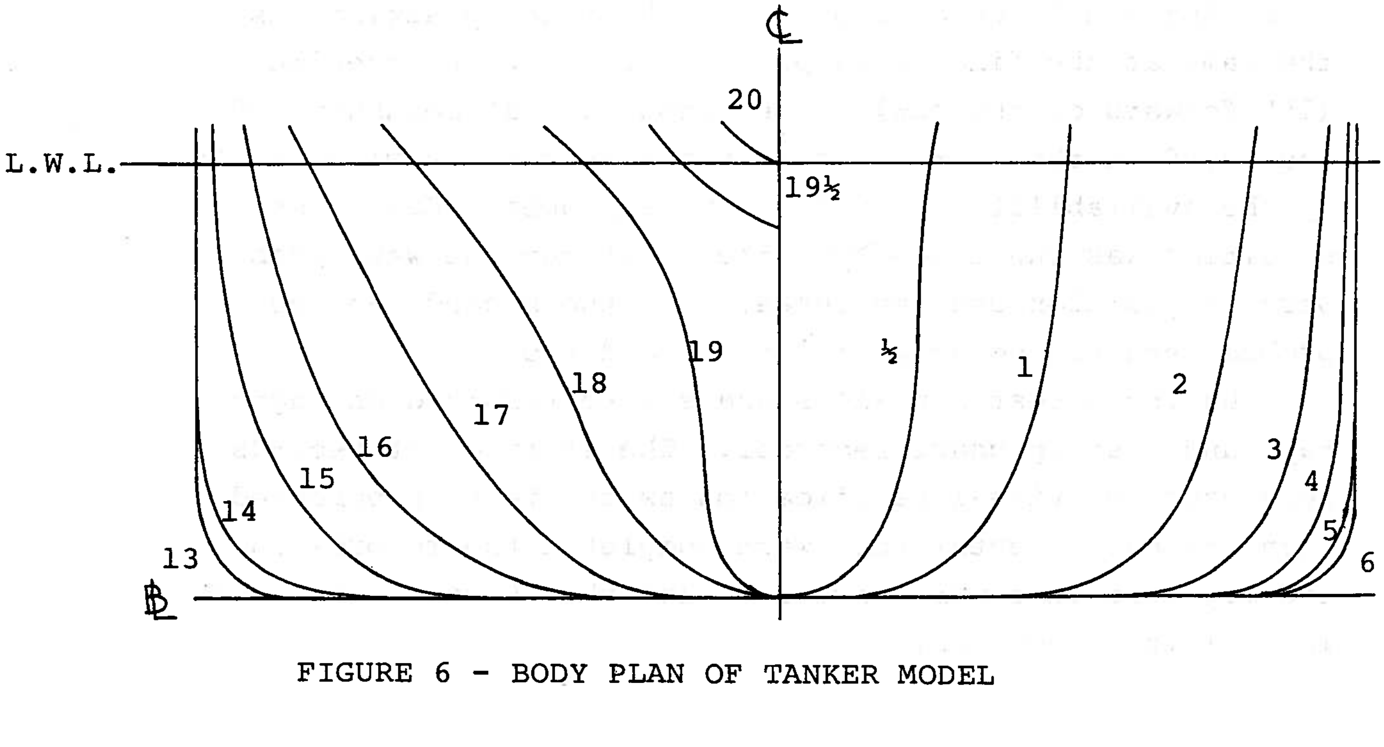

FIGURE 6 - BODY PLAN OF TANKER MODEL

The wave amplitude and motions were measured for each test condition using sonic wave probes and a gyroscope. The gyroscope was mounted at midship in the model and recorded the pitch amplitude. The wave probes were used to measure the wave amplitude, and the surge and heave motions. Unfortunately, there were only two wave probes so that each test condition had to be repeated twice. One probe always measured the wave amplitude 15" forward of the bow. The second probe measured the heave on one run and surge on the next. The heave motion was measured by hanging the sonic transducer above a 1 foot square plexiglass plate fixed horizontally in the model. For surge the plexiglass plate was mounted vertically and the transducer held in a horizontal position parallel to the water surface.

As discussed in Part I, the first harmonic of the wave amplitude changes as one moves down the tank. It was therefore necessary to measure the wave amplitude at several points along the ship length. This was accomplished by running the wavemaker at the frequencies for which the model would be tested without the model present. The wave amplitude was then measured at three points along the location where the model would be placed. The first position was the same as the fixed wave probe in the motion experiments (15" forward of the bow). The second was at amidship and the third at the stern. Again the measurements were limited by the availability of only two wave probes. Each test condition was run twice. On the first run the wave probes were at position one and three. On the second run the probes were placed at position one and two.

During a test run all signals were recorded on magnetic tape and a strip chart recorder. The strip chart records were used for visual verification as the tests progressed. When the experimental runs were completed the records on the magnetic tape were digitized and then Fourier analyzed in a digital computer.

The different test conditions for the experiments were chosen so that the effects of varying wave height, water depth and frequency could be measured. Two water depths were used, 6-1/4" and 8", corresponding to draft to depth ratios of .72 and .56 respectively. In order to vary the wave amplitude, two different strokes were set on the wavemaker. The actual measured wave amplitudes varied with frequency, but averaged approximately 1/2". The tests were conducted at the seven different frequencies shown in Table 3. Also presented in Table 3 are the corresponding nominal wavelengths computed using the linear shallow water dispersion relation presented in Part I.

TABLE 3

Experimental Test Frequencies

ω(rad/sec)	λ(ft);h=6 1/4"	λ(ft);h=8"
2.57	10.00	11.7
3.01	8.6	9.7
3.52	7.3	8.4
4.22	6.1	6.9
5.79	5.1	5.8
7.12	4.4	5.1

Presentation of Results

The results of the motion experiments and the theoretical predictions are shown in figures 7-12. The results are all plotted versus the nondimensional parameter L/λ, where L is the model length and λ is the nominal wave length listed in Table 3. Surge and heave are both nondimensionalized with respect to a representative wave amplitude, $\bar{\eta}_o$. Pitch is plotted as the parameter $\zeta_5 L/2\bar{\eta}_o$. For the plots, ζ_1, ζ_3, and ζ_5 are the first harmonic amplitudes of the actual response. $\bar{\eta}_o$ is an average of the wave's first harmonic amplitude over the length of the model.

The use of the first harmonics was necessated by the fact that pure sinusoidal waves can not be generated in shallow water. It can be shown that comparing the first harmonics of the input and output of a system yields the best possible (in a least squares sense) equivalent linear system [for example see Graham and McRuer (1961)]. By testing at different wave amplitudes and comparing the results, one can obtain a feel for the importance of the nonlinear elements in the system. If the system is linear with respect to wave amplitude the motion response amplitude divided by the wave amplitude will remain constant.

In the present set of experiments, the first harmonic was dominate. For the motion responses the second and subsequent harmonics were less than 10% of the first. The first harmonic of the wave amplitude was relatively less dominate. Thus, the model is acting like a low pass filter and not responding to the high frequency harmonics of the exciting wave.

As discussed in Part I, the amplitude of the first harmonic of the wave record varied as one moved along the model length. This variation in amplitude was at times as large as 35%. Thus, in arriving at an exciting wave amplitude for comparison with theory, an average was taken of the fundamental wave amplitude at the three wave probe locations along the model length. The phasing of the first harmonic components between the three locations was checked and found to be within 10° of the expected kx variation. The use of a simple average of the wave amplitudes, therefore, seem justified. Since there were only two wave probes available, each test case had to be run twice for wave calibration and twice again for the motion tests. The fundamental amplitudes as measured at the front probe had an average variation of 10% for the four test runs. If the four runs showed a variation of more than 15%, that particular test case was rejected. In arriving at an exciting wave amplitude, the results of the two wave calibration runs (without the model present) were scaled to agree with the motion tests.

The surge results for the two different water depths are plotted in figures 7 and 8. The results for only one plunger stroke are shown in each graph. Unfortunately, the results for the other stroke were lost. At T/h = .72 and a wave plunger stroke of 3/4", the wave calibration data was taken at an incorrect water depth so that the motion data can not be properly plotted. At T/h = .563 and a plunger stroke of 1 1/2" the surge motion at the low frequency end was so large that the model was hitting the sonic transducer and the test halted. From the figures it can be clearly seen that the surge motion is very small for high frequencies. For low frequencies the surge motion tends to become larger and larger.

The heave and pitch responses are shown in figures 9, 10, 11, 12. In figure 9 and 10 only one set of points is plotted because, as previously explained, the wave calibration at the 3/4" plunger stroke was incorrect. In figures 11 and 12, two sets of data points are shown. The circles are for a 3/4" plunger stroke. In general, the nondimensionalized motion amplitude for the two strokes are very close, indicating that the response of the model is linear with respect to wave amplitude. Both the heave and pitch motion tend to decrease with increasing wave frequency to a kind of null point and then increase again.

Also plotted in figures 7-12 are the theoretical predictions of the motion using Tuck's (1970) theory. The effects of the mooring lines were included in the calculations by considering them as linear springs. The differences in the computed motions with and without mooring lines are very small. Therefore, inaccuracies in the description of the mooring lines will have very little effect on the predicted motions.

Two curves are plotted for each case. The dotted curves are the first order results. For heave and pitch it

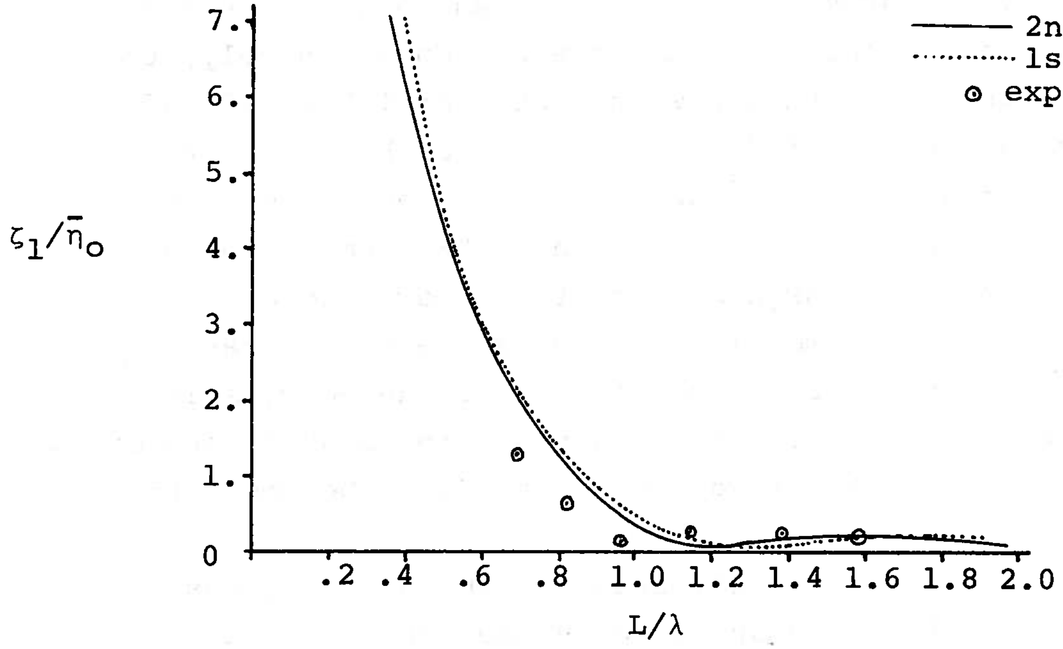

FIGURE 7 - SURGE ; T/h = .720

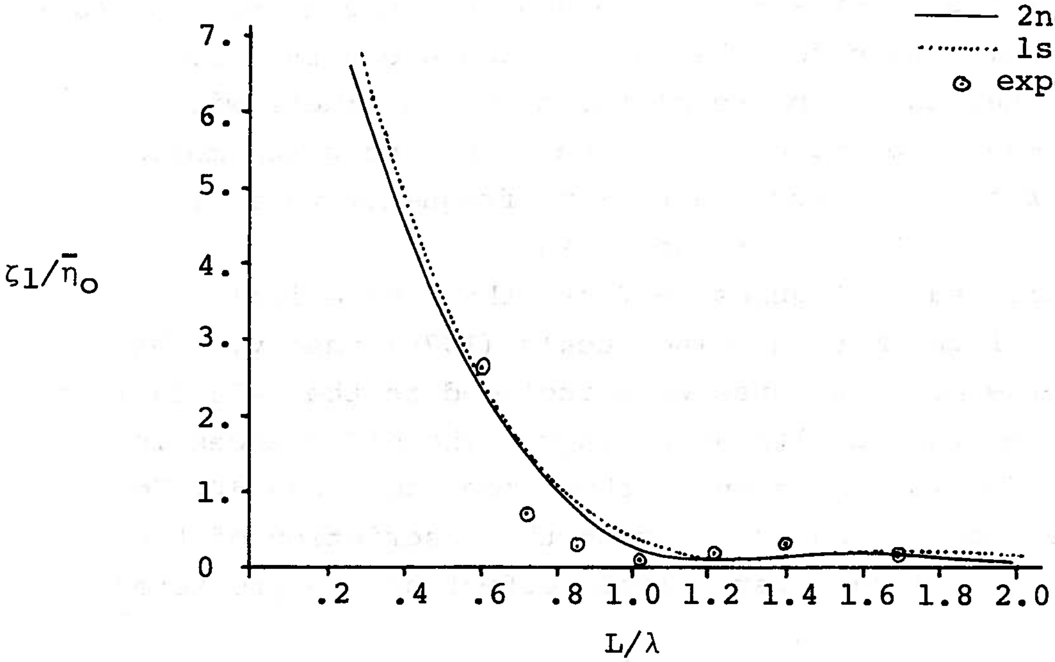

FIGURE 8 - SURGE ; T/h = .563

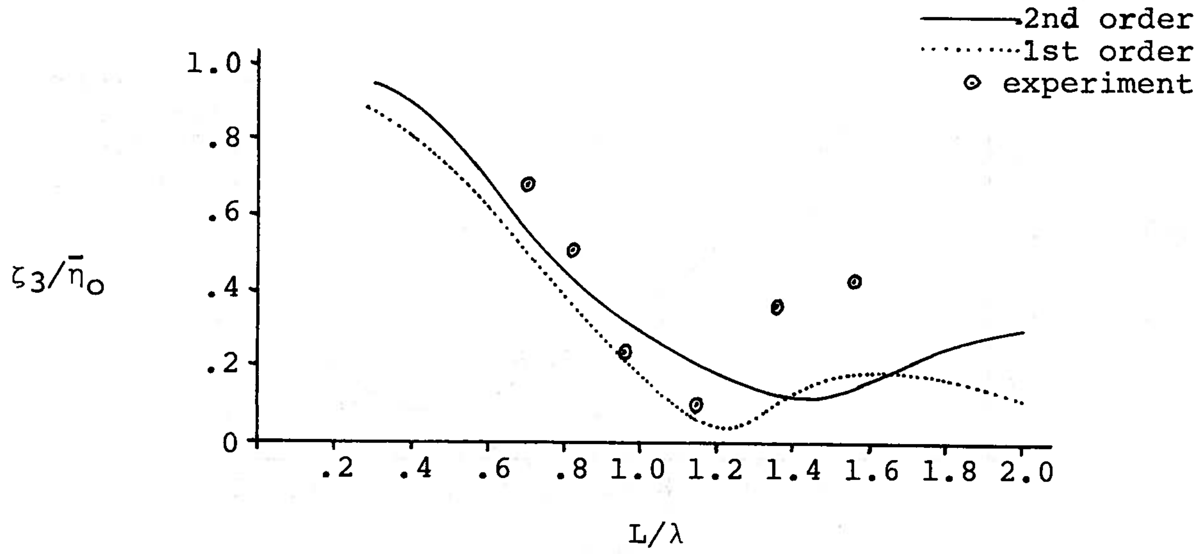

FIGURE 9 - HEAVE ; T/h = .720

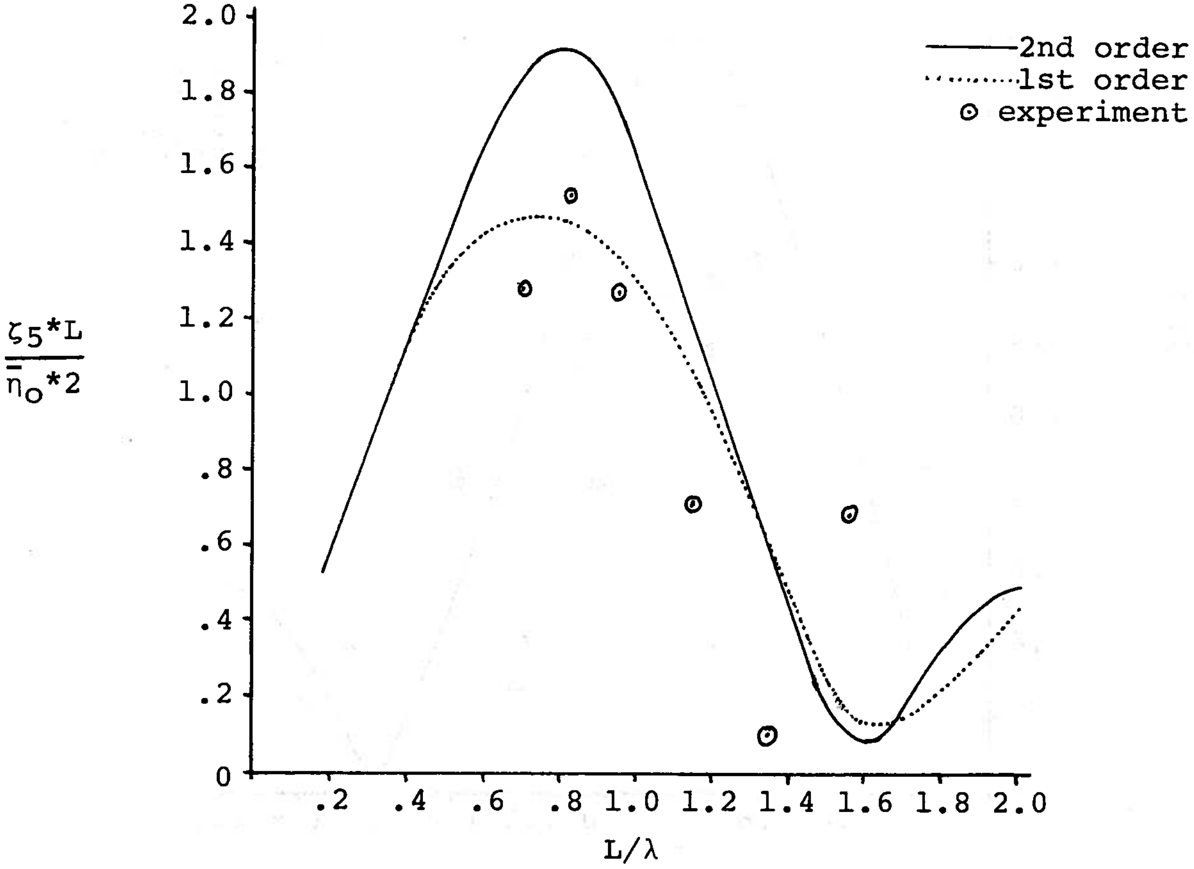

FIGURE 10 - PITCH ; T/h = .720

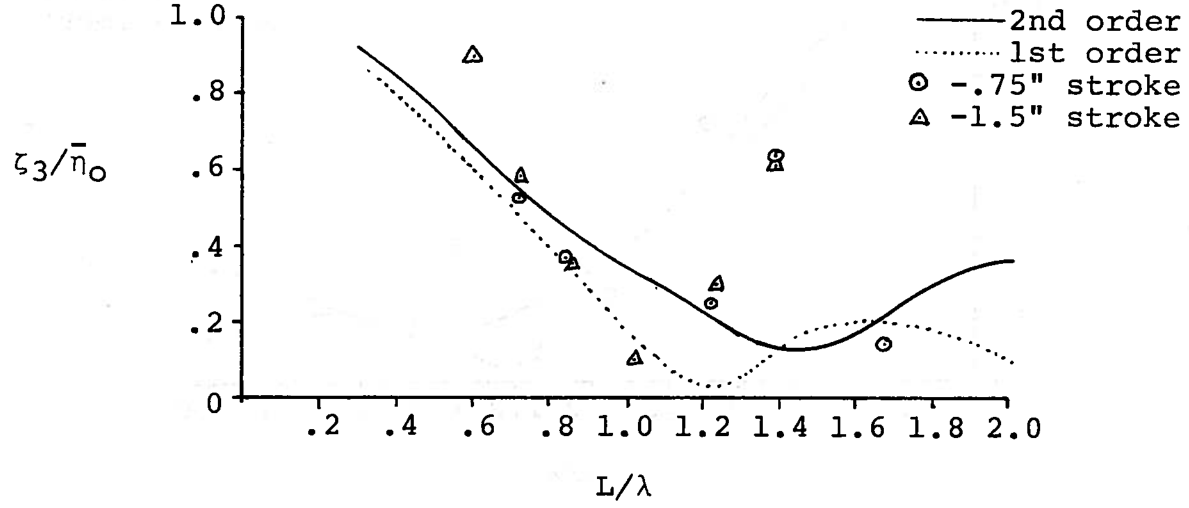

FIGURE 11 - HEAVE ; T/h = .563

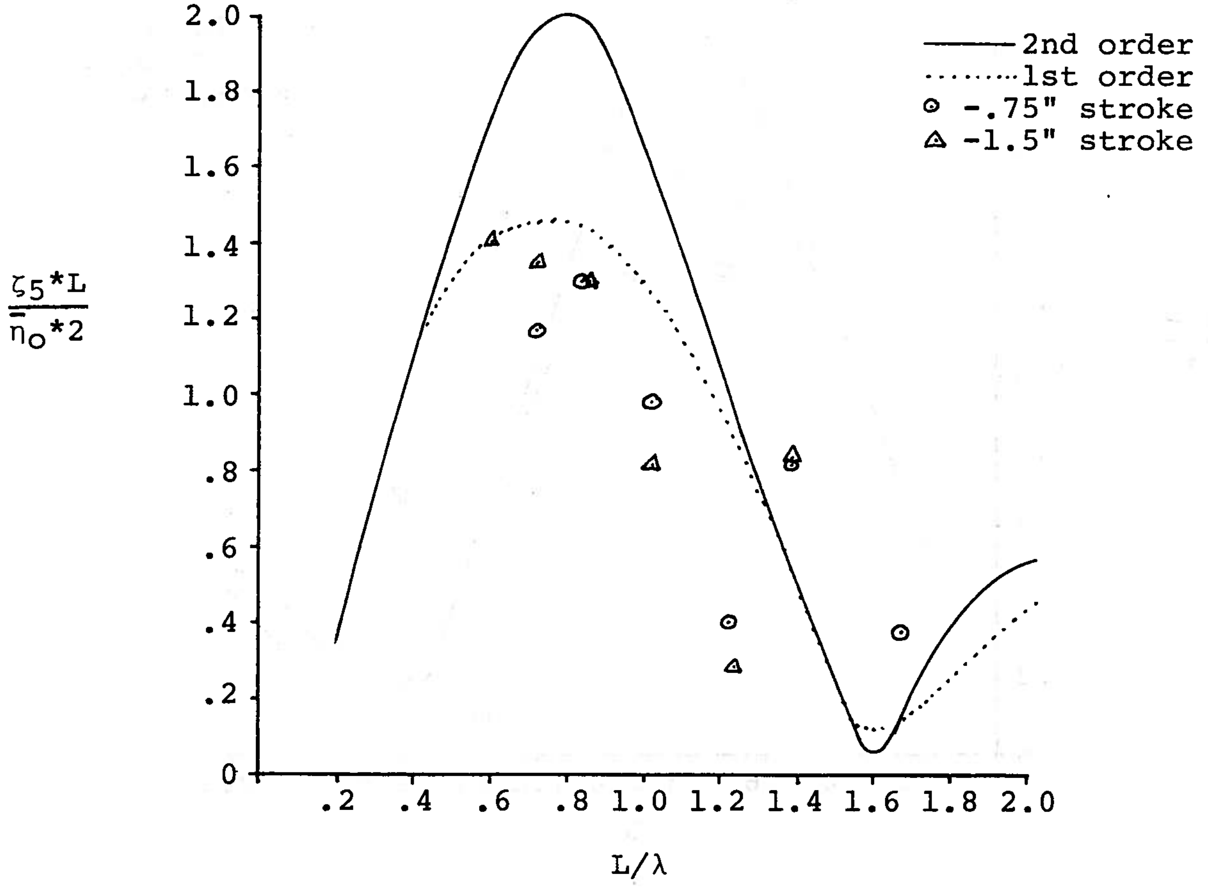

FIGURE 12 - PITCH ; T/h = .563

represents a balance between the Froude-Krylov exciting force and the hydrostatic restoring forces. For surge, it is a balance between the natural inertia force and the Froude-Krylov exciting force. The solid curves are the motion predictions using the complete second order theory of Tuck [see Beck and Tuck (1971)]. The second order theory includes the first order terms plus effects due to added mass, damping, and wave diffraction.

Discussion of Results

As can be clearly seen in figures 7-12, the theoretical predictions do not show particularly good agreement with experimental results. For surge, both theory and experiment indicate identical trends. They both show very little surge at higher frequencies and ever increasing surge at low frequencies. The predicted surge amplitudes are in reasonable agreement with experiments.

For heave and pitch the agreement is much poorer. In general, it appears the first order theory gives better agreement, but neither the first nor the second order predictions are very satisfactory. For heave, the null point in the experiments is shifted to a lower frequency and the experimental motions seem to be larger in the high frequency range. Strictly speaking the theoretical results are not valid in this region, because the water is too deep. The theoretical derivation assumes that shallow water wave theory is valid. This requires that the wave length be approximately ten times the water depth. For higher frequencies this is no longer true. It might be mentioned the Kim's strip theory predicts much higher heave amplitudes in the high frequency range for a Series 60, C_B=.70 ship [see for instance Beck (1973)]. A computer routine to calculate two dimensional, finite depth, added mass and damping is not available at the University of Michigan, and Kim's calculations have not been repeated for the present model.

For both heave and pitch, the experimental results indicate no clear trends of variation with water depth. One might say that at high frequencies the larger depth has greater motion and at low frequencies the two are about the same. However, the amount of data available is really too small to justify positive conclusions. From the theoretical side, the second order theory predicts that the motions should increase slightly with depth.

In comparison with theory the pitch results are the most disturbing. The second order theory predicts a large pitch amplitude around $L/\lambda=.8$, due to the effects of added inertia. Apparently these effects are never realized, since the experimental pitch amplitudes are even less than the first order results. The reasons for the differences between the theory and experiments are unclear. The added inertia is probably not as large as computed. Also, the exciting force might be much less than predicted. In this frequency range damping should have very little effect, since pitch reasonance is at higher frequencies.

Similar to heave, the pitch results also have a shift in the frequency of the null point in comparison to theory. The null point arises from the exciting force becoming very small. Thus, something is causing the exciting force to change from the theoretical prediction. The first order theory uses only the Froude-Krylov exciting force, which, except for the neglecting of the Smith effect, is accurately computed. The frequency shift must be caused by some type of diffraction wave effect. None of the presently available theories seem to account for this effect.

Conclusions

The primary conclusion to be gathered from this initial investigation is that much more work needs to be accomplished before we can accurately predict the response of a ship in shallow water to waves. The inherent nonlinearities associated with shallow water waves is one of the major problems. If we are to predict full scale ship motions, the effects of these nonlinear properties on the exciting wave spectra must be clearly understood. It appears from the experiments that while the exciting waves are nonlinear, the response of the model is linear with respect to wave amplitude. Thus, the use of a linear theory might give acceptable engineering results, assuming the exciting wave can be properly defined. The reason the responses are linear with respect to wave amplitude are not obvious. Perhaps the nonlinearities are unimportant in the near field so that the hydrodynamic forces acting on the ship are linear with wave amplitude.

In general the heave and pitch motion predictions were not good. Reasons for the discrepancies between theory and experiments are unclear. The use of a linear theory might be errorneous, but the experiments did show the motions to be linear with respect to wave amplitude. Since the frequencies at which the null points in the motion occur do not correlate between theory and experiment, the exciting force calculations are in error. A check on the exciting force calculations could be obtained by running a set of experiments in which the model is fixed and the exciting forces measured. Another source of discrepancy between theory and experiments could be the neglect of viscous stresses. In deep water, viscous stress are unimportant, except in roll. In shallow water, viscosity might possibly alter the flow between the model and the bottom of the tank. It appears, however, that this is not the case. If viscous forces are important, one would expect the motions to radically change when the gap between the model and the bottom is more than doubled. The experimental motions exhibited hardly any change between the 6 1/4" and 8" water depths.

Before any definite conclusions can be drawn, more experiments should be conducted. The present set of experiments were intended as an introduction to the problems of conducting shallow water motion experiments and to obtain preliminary data with which to compare the theory. In this sense they have been eminently successful. In future experiments more instrumentation will be needed. The wave amplitude should be measured at more than 3 points along the length of the model, so that the exciting wave amplitude can be better understood and defined. A rake of wire wave probes might prove successful. Furthermore, the motion amplitudes should all be measured simultaneously. This would require more instrumentation than was available. Finally, Fourier analyzing the experimental records and comparing the first harmonics appears to work well as long as the exciting wave amplitude can properly be defined. It is not really clear that averaging the local wave amplitudes gives a representative exciting wave amplitude. This should be verified through analytical studies.

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The results of an experimental investigation into shallow water ship motions are presented. The experiments were conducted in two parts. In the first part, the change in form of sinusoidally generated waves as they travel in shallow water were measured. The results are presented as changes in the Fourier harmonics with distance from the wave maker. Comparisons with theoretical predictions from the Korteweg - de Vries equation are made and show good correlation.

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20. In the second part of the experiments, measurements were made of the surge, heave and pitch motions of a tanker model in response to shallow water waves. Because the exciting waves are not sinusoidal, the waves and motion responses were Fourier analyzed. The first harmonic amplitudes were then considered to be the equivalent linear responses. The experimental results are compared with theoretical predictions made by a slender body theory of shallow water ship motions. The surge theoretical results are in reasonably good agreement with the experiments. The heave and pitch agreement is poor.

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